



# Bioaerosols associated with animal production operations

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## ABSTRACT

Air emissions from animal housing and manure management operations include a complex mixture of biological, microbial, and inorganic particulates along with odorous volatile compounds. This report highlights the state of current issues, technical knowledge, and remaining challenges to be addressed in evaluating the impacts of airborne microorganisms, dusts, and odorants on animals and workers at animal production facilities and nearby communities. Reports documenting bioaerosol measurements illustrate some of the technical issues related to sample collection, analysis, as well as dispersion and transport to off-farm locations. Approaches to analysis, mitigation and modeling transport are discussed in the context of the risk reduction and management of airborne spread of bioaerosols from animal operations. The need for standardization and validation of bioaerosol collection and analytical techniques for indoor as well as outdoor animal agriculture settings is critical to evaluation of health effects from modern animal production systems that are increasingly situated near communities.

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## 1. Introduction

The size and geospatial distribution of livestock and poultry operations continues to respond to demographics, land pressure, and economic development. Existing trends toward intensification and industrialization of meat animal production are projected to increase globally. Microbes of concern in animal production have been studied by veterinary, public health, sanitation and agricultural scientists (Smith et al., 2005; Strauch and Ballarini, 1994). Animal confinement tends to increase the overall microbial load in the immediate production environment by virtue of the increased volumes of feed, animals, and organic residuals (manure and wastewater) present, and the increased handling and management required. With more animals, materials, equipment, and workers in the production facility, there is a concurrent increase in three distinct yet interrelated types of airborne materials: (1) bioaerosols, (2) dust (mineral particulates serving as carriers), and (3) odorous volatile compounds.

Animal housing typically exposes animals and workers to substantial concentrations of volatile compounds ( $\text{NH}_3$ ,  $\text{CH}_4$ , numerous organics, and  $\text{H}_2\text{S}$ ), dust (fine particulates, endotoxin, animal dander, animal feed and excreta), and a variety of bioaerosols (bacteria, endotoxin, viruses, parasites, fungi, mycotoxin, insect parts, pollen, and grain particles) that can have adverse health effects (Clark et al., 1983; Cole et al., 2000; Douwes et al., 2003; Nowak, 1998; Zejda et al., 1994). Bioaerosols initially generated indoors may disperse outdoors. Manure application to fields may generate

bioaerosols, dust, and odors that transit to and beyond a property boundary. The impacts that new technologies to mitigate biological, nutrient, or odorant concentrations in animal production facilities, have concurrently on bioaerosols, dust, and odorant compounds will continue to require evaluation.

This report highlights the state of current issues, technical knowledge, and remaining challenges to be addressed in evaluating the relationships among airborne microorganisms, dusts, and odorants on animals and workers at animal production facilities and nearby communities. Reports documenting bioaerosol measurements illustrate some of the technical issues related to sample collection, analysis, as well as dispersion and transport to off-farm locations. Approaches to analysis, mitigation and modeling transport are discussed in the context of the risk reduction and management of airborne spread of bioaerosols from animal operations.

## 2. Bioaerosols, dust, and odor relationships

### 2.1. Bioaerosols

Bioaerosols comprise the submicron,  $<0.02 \mu\text{m}$  (viruses, endotoxin, and mycotoxin), to multi-micron,  $0.2\text{--}50 \mu\text{m}$  (bacteria, fungi, parasites, and algae), biological particulates suspended in air, as live or dead intact microbes or their constituents/fragments, which may also include endotoxin, mycotoxins, insect parts, pollen, grain and microbial proteins (Cox and Wathes, 1995). Bioaerosols may be generated either as liquid droplets or as dry materials and transit in air either individually, as clusters, or on 'rafts' of organic matter. While bioaerosols are ubiquitous in ambient air and are carried short and long distances by small and large air currents (Brown

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Mogens and Hovmøller, 2002; Jones and Harrison, 2004; Lighthart and Mohr, 1994), the types and amounts can vary considerably in space and time depending on several physico-chemical factors. In general, confined animal operations and the generation of bioaerosols, dust, and odors have accentuated the need for development of sustainable solutions to reduce adverse health impacts from these constituents on workers, animals, and nearby communities (Clark et al., 1983; Cole et al., 2000; Douwes et al., 2003; Nowak, 1998; Seedorf et al., 1998; Zejda et al., 1994).

In ambient indoor and outdoor air, except when a source is nearby, concentrations of potential public or veterinary pathogens generally are very low or absent. Several studies have been conducted to determine the extent to which bioaerosols generated at animal production facilities are significantly different from those in the general ambient air. Table 1 shows examples of the ambient airborne concentrations of cultured microorganisms reported from various animal confinement (indoor) situations in which reduction technologies have yet to be implemented.

#### 2.1.1. Bioaerosol mitigation

More information is needed to understand and design air quality management technologies (indoor or exhaust systems) that are effective in reducing bioaerosols. Reports indicate that some systems function satisfactorily under standard operations for removal or control of contaminants like odor and particulates, but can fail to control emissions of certain pathogenic agents responsible for animal disease outbreaks. This has important implications for emergency preparedness, and animal disease epidemic management. For example, a dual bioscrubber–chemfilter system operating to reduce odor and ammonia emissions also significantly reduced emissions of airborne dust, endotoxins, and bacteria at a duck fattening facility (Zucker et al., 2005). However, Aarnink et al. (2005) reported that existing odor and  $\text{NH}_3$  scrubbers, failed to prevent bioaerosol emissions during a swine fever outbreak in the Netherlands. They determined that supplementation of the sulfuric acid in existing scrubbers with peracetic acid in times of high risk of disease outbreak would be the most cost-effective way to prevent spread of the disease agent, because this more effective

disinfectant would be impractical and cost prohibitive for continuous use.

#### 2.2. Dust

Dust as fine particulates varies in shape, size, and composition, but can enter and deposit in the upper airways and deep lungs (ACGIH, 2006). Deposition site depends on size and may range from inhalable ( $\leq 100 \mu\text{m}$  aerodynamic diameter ( $d_{ae}$ )), thoracic ( $\leq 10 \mu\text{m}$   $d_{ae}$ ) to respirable ( $\leq 5 \mu\text{m}$   $d_{ae}$ ). Although fine particulates may be composed of inorganic or organic constituents, microorganisms (live or dead, whole or fragmented) may be enmeshed or attached to them. Such fine particulates may also have volatile compounds such as  $\text{NH}_3$  or a range of organic compounds adsorbed to them (Bottcher et al., 2004; Schiffman et al., 2000; Schiffman and Williams, 2005). In people, long-term exposure to such dusts can cause respiratory damage, and in the short-term, effects can result from daily workshift exposure  $<1.0 \text{ mg/m}^{-3}$  respirable dust. Symptoms in workers may include: bronchitis, hyperactive airways disease, atopic asthma, acute organic dust toxic syndrome, chronic organic dust toxic syndrome, mucous membrane irritation, increased susceptibility to other chest illnesses, chronic sinusitis, a byssinosis-like condition, nausea, diarrhea, rhinitis, fatigue, eye and throat irritation, headache, shortness of breath, wheezing, dizziness, and sleep disturbances. This extensive list of symptoms reflects the vast number of potential bioactive constituents in dusts.

From the perspective of occupational exposure in agricultural settings, endotoxin is probably the most relevant parameter so far identified with respirable particulates and associated with lung function impairment (Nowak, 1998; Spaan et al., 2006). Its microbial origin, ubiquity, persistence, and capacity to attach to substances and particulates makes it a challenging material to control in agricultural operations. As noted by Spaan et al. (2006), agricultural industries in general often exceed the Dutch proposed occupational exposure limit ( $50 \text{ endotoxin units-EU m}^{-3}$ ) and temporary legal limit ( $200 \text{ EU m}^{-3}$ ) for airborne endotoxin. The latter is a primary example of a material which is in part a bioaerosol (because it is microbially derived) and a dust (because

**Table 1**  
Bioaerosol concentrations indoors at various types of animal production facilities.

Animal	Microbes	Concentration (cfu/m <sup>3</sup> air)	Sampler type	Reference
Dairy	Total	$1.5 \times 10^7$	Filtration	Larsson et al. (1988)
Swine	Total	$1.5 \times 10^5$	Impactor (An6 <sup>*</sup> )	Cormier et al. (1990)
	Gram-negative	80		
	Fungi	$1.5 \times 10^2$		
Swine	Total	$1.1 \times 10^5$	Impactor (An6)	Heederik et al. (1991)
	Gram-negative	$7.7 \times 10^3$		
Swine	Total	$3.0 \times 10^5$	Impinger, Filtration	Clark et al. (1983)
	Gram-negative	$8.8 \times 10^4$		
	Fungi			
Poultry-caged layers	Total	$7.7 \times 10^6$	Cyclone	Hinz and Linke (1998)
	Gram-negative			
Swine	Total	$6.6 \times 10$	Filtration, Impactor (An6)	Predicala et al. (2002)
		$8.6 \times 10^4$	Filtration, Impactor (An6)	
	Respirable	$9.0 \times 10^3$		
		$2.8 \times 10^4$		
Swine	Total	$6.8\text{--}9.0 \times 10^4$	Impactor (Slit)	Banhazi et al. (2005)
– Unbedded		$2.17 \times 10^5$		
– Bedded				
Swine	Total bacteria	$1.3 \times 10^4$	Impactor (An1 <sup>*</sup> )	Kim et al. (2008)
	Total fungi	$1.3 \times 10^3$		
Swine	Total bacteria	$2.9\text{--}3.8 \times 10^4$	Impactor (SAS100 <sup>**</sup> )	Pavićić et al. (2008)
	Total coliform	$5.8\text{--}6.9 \times 10^2$		
	Hemolytic bacteria	$3.4\text{--}4.4 \times 10^3$		
	Fungi	$4.4\text{--}5.5 \times 10^2$		

<sup>\*</sup> An6, Andersen, 6-stage impactor; An1, Andersen, 1-stage impactor.

<sup>\*\*</sup> SAS100, the manufacturer and model of impactor.

of its size and nonviable nature). Seedorf et al. (1998) reported from a survey of cattle, pig, and poultry housing units in four European countries that cattle houses had the lowest endotoxin concentrations whereas poultry houses had the greatest with a mean of 692 and 49 ng/m<sup>3</sup> for inhalable and respirable particulates, respectively.

Occupational standards specify threshold limit concentrations for airborne respirable dust and protection of workers (AGCIH, 2006) and standard methods for collection and measurement of respirable dust are available (NIOSH, 1994; Phillips et al., 1998). However, differences in collection efficiencies have been reported for several personal samplers in use, and work-specific conversion coefficients to normalize estimates of worker exposure to total dust from measurements using various dust sampling devices have been derived and suggested by Predicala and Maghirang (2003). In addition, O'Shaughnessy et al. (2007) provided a method for correcting a sampler-to-sampler ratio to deal with changes in size distribution of aerosols that can be used in most conditions, provided initial comparisons are normalized with the same dust.

### 2.2.1. Dust mitigation

In general, with adequate ventilation of animal housing, decreased stocking density, and structural and regular management of manure exposure to dust and endotoxin can be minimized (Banhazi et al., 2005; Duchaine et al., 2000). Canola oil spray reduced dust in swine barns and reduced acute health effects in naive healthy workers (Senthilselvan et al., 1997). Spraying rape seed oil daily was more effective at reducing aerial dust concentrations than adding 4% fat to the swine diet, resulting in 75% and 50% reductions in dust, respectively (Pedersen, 1998). Electrostatic space charge systems have shown promise in reducing dust in poultry houses (Ritz et al., 2006; Mitchell and Baumgartner, 2007). Similarly, electrostatic charge systems were also shown to reduce *Salmonella* spp. by 50% in chicks and in their ceca (Gast et al., 1999), while also reducing dust concentrations. As these and other mitigation technologies are developed and evaluated further, it will be important to determine their effects on the emissions of bioaerosols, pathogens and their viability/infectivity, endotoxin, and odorants.

### 2.3. Odorous volatile compounds

Odors are a perceived response (Schiffman and Williams, 2005) to certain volatile organic compounds (VOCs), but these odorants (the compounds) are not necessarily correlated with the presence or amounts of pathogens or fecal indicator microorganisms in the materials (Kim et al., 2005), particulate matter, or endotoxin. Human panels, olfactometry standards and practices, and GC–MS analysis (Schiffman et al., 2001; Zahn et al., 1997) coupled with sniffing ports have aided evaluation of the odor response in connection with animal facility odorant concentrations.

All animal operations generate odorous volatile compounds from microbial metabolism of the various organic materials present in the systems, including feed, bedding, and excreta. Many of these compounds are detectable at exceedingly low concentrations (Millner and McConnell, 2000; Ruth, 1986; Schiffman et al., 2000). Schiffman et al. (2001) reported 331 different VOCs and fixed gases from swine facilities. In confined interior spaces with intensive animal stocking densities, some odorous compound concentrations (NH<sub>3</sub> and H<sub>2</sub>S), can accumulate rapidly and become a respiratory hazard for workers and animals. Beyond animal facility perimeters per se, however, odor complaints often lead to complaints about feeling ill (health symptoms), which in turn lead members of surrounding communities to express concerns about infection or toxicity from exposure to what may be transported in the air along with the odorants. Schiffman et al. (1995) have reported that these and other con-

cerns and responses to perceptions of odor are significantly associated with mental health consequences, such as increased tension, depression, fatigue, confusion, and mood changes. Such responses also match closely those reported for nuisance odors.

Schiffman and Williams (2005) described three mechanisms by which ambient odors might elicit health symptoms: (1) exposure to odorous compounds elicits a response in the trigeminal nerve system referred to as an irritation effect (irritation causes the health symptoms, whereas odor is the exposure marker); (2) at nonirritant concentrations exposure elicits an innate, learned aversion; (3) copollutants (such as endotoxin) elicit a health symptom response. They note that objective bio-markers of health symptoms are needed, to determine if and when health complaints constitute health effects. For these reasons, measurements of volatile compounds, dust (particulates which can absorb and re-volatilize compounds), odor, and irritation are needed along with measurements of bioaerosols and endotoxin to discern the contribution of each and the health effect. An additional factor that complicates the situation is that odorous compounds, even when individually present below their irritant threshold concentrations, can when present in mixtures collectively exceed an irritant threshold concentration and thus elicit a response in a sensitive receptor (Korpi et al., 1999).

### 2.3.1. Odor mitigation

As noted above, biofilters and chemical air scrubbers may be effective in reducing emissions of odorous compounds from animal production facilities. In general, with adequate ventilation and regular management of manure in animal housing, H<sub>2</sub>S and NH<sub>3</sub> may be maintained below 20 ppm and 10 ppm, respectively, and thereby avoid adverse respiratory responses to these hazards in workers and animals. However, effects of technologies like ventilation and practices on mitigating bioaerosols and endotoxin must be evaluated to determine the potential for health effects from chronic exposure to low concentrations.

Loughrin et al. (2006) reported substantial reductions (83–97%) in lagoon liquid odorants, *p*-cresol (83%), 4-ethylphenol (93%), and skatole (97%) resulting from a multi-stage swine manure treatment system. In studies of ambient air outside swine facilities, Lemay et al. (2007) found that NH<sub>3</sub> and H<sub>2</sub>S are rapidly diluted well below toxic concentrations. Nonetheless, because adsorption of compounds to particulates that are highly respirable and exposure to other kinds of volatile organic compounds has been shown to influence immune response, Schiffman and Williams (2005) noted that more research is needed to evaluate these types of impacts on human health.

## 3. Bioaerosol collection and analyses in animal stables and farms

Microbial samplers available to collect bioaerosols include single and multi-stage impactors, impingers, filters, cyclones, vertical elutriators, and electrostatic precipitators. Details of each are described by Cox and Wathes (1995) and Henningson and Ahlberg (1994). Most have been used to assess exposure concentrations indoors in workplaces, homes, and schools and have been extended for use in outdoor air, although their efficiencies in outdoor settings, in which variable air speeds and directions occur, have not been well documented.

With specific regard to bioaerosols, there is a notable absence of standardized and validated methods for enumeration of various types of microorganisms in outdoor bioaerosols. Although various methods and devices have been used to detect and quantify outdoor bioaerosols, results show a wide range in values for prevalence and concentration across very diverse types of animal

operations and landscapes. Without doubt, standardization and validation of collection and sample analysis protocols are currently the most important technological factors that needs to be resolved with regard to outdoor bioaerosol investigations. Until a standardized, validated methods are established for each of the microbial types or groups (bacteria, fungi, viruses, protozoa, and endotoxin) in outdoor air, then studies will continue to be of value only on a comparative basis within the context of the factors tested at the same site. Cross-site comparisons and multi-institutional datasets which eventually may be needed for development of standards and practices or regulatory compliance will require standardized, validated methods, devices, and protocols. A major difficulty that needs to be confronted from the fact that no single sampling approach, either impaction, impingement, filtration, centrifugation, or passive, is suitable for all groups of microbes. Each microbial group, and even within groups, has inherent survival limits that need to be matched with the type of sampler and the stress that it imparts to the particles during the collection process. As molecular methods have advanced, there are increasingly greater opportunities and examples for the utilization of identification approaches in the presence, concentration, and survival of the microflora in air. Additional research and development is needed to advance beyond the traditional culture-based methods for detection and quantification.

Advanced devices that take advantage of culture-independent techniques are being developed to help overcome the time lag inherent in existing bioaerosol protocols (Agranovski et al., 2006). Bioaerosol concentration studies often show large variations in samples, even with indoor air in adjacent locations (Toivola et al., 2002). Consequently, bioaerosol study designs need to include quality assurance (duplicates and field blanks) for the specific microbial targets being measured. Methods for endotoxin determinations from air samples also have recently been reviewed and evaluated (Spaan et al., 2007).

Cultivation-independent surveys of small-subunit rRNA genes used to assess total bacterial and fungal bioaerosol constituents have revealed a greater species richness than traditional culture-dependent methods, and in some cases show 100- to 1000-fold greater diversity (Brodie et al., 2007; Després et al., 2007; Nehme et al., 2008). Fluorochromes also offer an alternative sensitive tool for detection and culture-independent quantification that detects relationships to important atmospheric physical factors (temperature, rainfall, and UV light) to which culture-dependent factors are relatively insensitive (Chi and Li, 2007). Maron et al. (2005) using culture-independent analyses determined that the majority of the identified bacteria were soil or plant associated. Thus, they concluded that the bioaerosols originated from local sources. In contrast, results from molecular approaches to bioaerosol analyses led Fierer et al. (2008) to conclude that short-term temporal variability in bacterial diversity was associated with location in ambient outdoor air.

## 4. Dispersal and transport

### 4.1. Land application

Manure management and application on fields is accomplished in a wide variety of ways on different animal production facilities, including: lagoons, solids stacking, sprinkler irrigation of liquids with forced-projection or center-pivot equipment, injection of slurries, slurry irrigation from vehicle mounted spray nozzles, and land application of solids with box-beaters, side discharge units, or V-box spreaders (NRAES, 1994).

Land application of lagoon sludge (solids 6–13%) may only occur once a year or less, but is inherently an aerosol and odor gen-

erating process. The three main materials-handling approaches used for this liquid include: (1) pumping slurry through a large bore gun-sprinkler system on cropland followed by soil incorporation; (2) initial dewatering and subsequent manure spreading on fields; (3) dewatering and direct placement on cropland by spreaders equipped to handle slurries. Where injection can be used, aerosolization potential may be considerably reduced. In systems that separate solids from liquids for beneficial use (such as bedding materials, supplements to animal feed rations, composting, and soil amendments), separators can readily be enclosed to minimize aerosolization.

Boutin et al. (1988) conducted an extensive series of bioaerosol tests during land application of cattle and swine slurry with mobile and stationary farm equipment. They reported that total bacterial counts in air at the edge of the applied areas was  $>2000/\text{m}^3$ , and no pathogenic bacteria were recovered. High pressure spray gun systems that discharge the liquids upwards results in substantial droplet size reduction and drift, whereas tank spreading reduced the spray area arc and drift, resulting in reduced airborne bacteria concentrations relative to the spray gun.

The physical characteristics of municipal wastewater treatment solids (biosolids) are similar to manures treated with flocculating agents to increase solids content. Results from biosolids land application studies suggest that microbes in such moist, sticky, viscous types of materials are attached closely to sludge particles, and that the density propels the particles to a rapid deposition on the land rather than keeping them suspended in long-distance off-site transport (Brooks et al., 2005).

For relatively dry materials, like poultry litter, where screens, separators, and box spreaders are used, bioaerosol generation will occur and may result in longer distance transport due to its lower density and propensity to finer particles. Depending on the material and its stability these operations may also be accompanied by the release of odorant compounds that are detectable in the parts-per-billion range. In these cases, odorants that reach neighboring communities will elicit concerns as described above for odors. Limited data are available by which to clearly assess the risk to all segments of the receptor communities. Recent information relative to asthmatic children (Hoopmann et al., 2006) and exposure to bioaerosols from livestock operations points to the need for further evaluation of this subgroup to bioaerosols, dust, and odorants. These same issues apply to land application of manures and other organic residuals (Gerba and Smith, 2005; Boutin, 1988).

### 4.2. Modeling

Major interest in airborne survival and transport of microorganisms arises in connection with public health pathogens and zoonotic diseases. The focus in such cases is on minimizing dissemination of infectious agents and avoiding disease in animals or humans (Donaldson et al., 2001; Gloster et al., 2003; Harvey et al., 2007). In an effort to enhance preparedness and epidemic management, atmospheric transport models have been developed and applied to specific microbial agents (Cannon and Garner, 1999; Mayer et al., 2008). Transport principles and factors applicable to fine particulates are equally useful with odorous volatiles and bioaerosols which are often released simultaneously from the same materials-handling operations. In the past, bioaerosol modeling has relied heavily on standard Gaussian dispersion models with modification to account for die-off of microbes during air transit as a result of exposure to UV radiation, temperature, and desiccation (Lighthart and Mohr, 1994). A die-off constant for *E. coli* was reported as  $8.8 \times 10^{-3} \text{ s}^{-1}$  for morning, and  $6.6 \times 10^{-2} \text{ s}^{-1}$  for afternoon (Teltsch et al., 1980). Clearly, using a resistant spore-former such as *Clostridium* spp., which would be expected to easily survive ambient atmospheric stressors, as a surrogate for off-site



transport would provide a poor estimate of survival of non-spore formers, like *E. coli* and *Salmonella* spp., at distant downwind locations.

A variety of dispersion models, including Lagrangian, computational fluid dynamic, and modified Gaussian plume and puff models have been developed to deal with short and long range transport for epidemic management as well as odorous and pollutant compounds, and dust, from animal operations (Mayer et al., 2008; Minyoung et al., 2007; Nimmermark et al., 2005; Schiffman et al., 2003). For foot-and-mouth virus, local winds have a major influence on its dispersal and canalization of air flows in valleys accentuates the movement and concentrations (Mayer et al., 2008). With impinger collections from a center-pivot drop-nozzle irrigation system distributing swine lagoon liquid, Minyoung et al. (2007) reported increased total coliforms at 7.62 m downwind of the source, but at larger distances (70 m) concentrations were equivalent to those upwind. Wind direction variability during sampling periods coupled with the moving source presented unique sampling challenges. Similarly challenging is the situation with a tank truck moving while spraying liquid dairy slurry. In that case, impingers and high volume cyclone samplers were mounted on the front of an all-terrain vehicle which followed the tank truck at the downwind edge of the spray deposition. Total bacteria and coliform concentrations ( $2.5 \times 10^3$  and  $3.5 \times 10^2$ ) were 100–1000 times more concentrated than upwind or the 50 and 200 m downwind samples (Millner, data unpublished), which is consistent with values reported by Boutin et al., 1988. In other studies, Köllner and Heller (2006) calculated using VDI guidelines (VDI, 2007) that total airborne bacterial concentrations downwind of animal farms in the Northern Rhine Westphalia region reached background density at a distance of 420 m from the farm. However, the greatest concentrations were found 50 and 75 m away from the facility.

An alternative approach to bioaerosol assessment as described by Paez-Rubio et al. (2006) relies on estimating aerosol source concentrations and emission rates by both reconstruction and correlations between bulk soil/solids mixture content and emission rates. They suggest that this approach would eliminate the need to directly measure pathogens or toxins in aerosols and thereby avoid difficulties and limitations associated with monitoring low aerosol concentrations of toxic compounds and pathogens. They applied this approach to estimating aerosol source concentrations and emissions rates with data on soils and biosolids and showed that diskings presented the major biosolids-derived bioaerosol activity.

## 5. Summary

Quantifying the airborne constituents in the occupational environment by determining bioaerosols, dust, and odorants (volatile compounds) has important implications for evaluating the potential health risk to exposed people and animals and to animal productivity. Evaluating the exposure to known health hazards in the work environment allows identification of minimum achievable levels of exposure to the hazardous agent that are compatible with the suite of activities and management practices (new and old) in the production cycle. As new management practices are implemented, their effectiveness and impacts can be determined and possibly improved to meet target action levels. With land application of manure, clearly a liquid that has been treated to significantly reduce the number of fecal indicator microorganisms and/or pathogen concentration would be an example of a best available practice. Such treatment is unlikely to eliminate endotoxin. However, with unconstrained atmospheric dilution outdoors, maintaining elevated concentrations of temporary releases of endotoxin would be difficult. Odorants may remain a challenge for land application of unstabilized liquids in developed locations with residents nearby. Data on land spreading of poultry litter,

which is very dry and prone to generation of particulates, and quantitative bioaerosol emission data could be used to determine if modifications in spreader equipment might reduce bioaerosols, endotoxin, and dust from this manure management operation.

Multi-analyte approaches to air emissions have emerged through the efforts of various research centers and collaborations (Hinz and Linke, 1998; Phillips et al., 1998; Seedorf et al., 1998; Vanotti et al., 2007). Continued work within a framework that targets analyses of all these major airborne constituents that contribute to the air quality of workers, animals, and the community, is needed to support the evaluation, design and improvement of modern animal production systems that are increasingly situated near communities.

## 6. Conclusions

Future bioaerosol studies of animal operations need to emphasize:

- (1) Standardization/validation of collection methods, appropriate for microorganisms of concern, including indoor and outdoor settings.
- (2) Standardization/validation of analytical techniques, using molecular and advanced rapid technologies appropriate to target microorganisms.
- (3) Evaluation of effects of new mitigation technologies during and after their development on bioaerosols, dust, endotoxin, and VOC concentrations, using standardized/validated collection/analytical techniques, along with odor assessments, and emphasis on health impacts on animals and their growth and on susceptible individuals such as asthmatic children, elderly persons, and those with respiratory and immune deficiencies in communities near animal operations.

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